Acoustic Resonance Classification of Swimbladder-Bearing Fish at Multiple Scales

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LONG-TERM GOALS

Accurately describe the spatial and temporal distributions of fish and quantify the mid-frequency clutter characteristics of fish.

OBJECTIVES

To conduct a new class of quantitative studies of acoustic scattering by swimbladder-bearing fish utilizing new broadband-acoustic technology that is optimized for use in the resonance scattering region of fish. The studies, which include use of a long-range horizontal-looking system and a short-range downward-looking system, exploit the resonance scattering of the fish to significantly reduce ambiguities in the interpretation of the data.

APPROACH

Building on the success of three previous major experiments, which includes the NRL pilot measurements in 2008, we have made a fully-integrated set of measurements through two dual-ship experiments (Sept. 2010 and Sept. 2011) involving a NOAA fisheries vessel and a UNOLS vessel. We are exploiting the broadband capabilities of each of the mid-frequency acoustic systems (WHOI-Edgetech and NRL systems), along with their complementary deployment geometries (short-range downward-looking vs. long-range horizontal-looking, respectively) for both resonance classification of swimbladder-bearing fish and characterization of their patchiness at different spatial and temporal scales. Province-wide variability of the fish distribution, resonance signature, and clutter features are

studied with the long-range system while the strong depth dependence of the resonance, multiple resonances associated with mixed assemblages, and short-range patch structure (in the vertical plane) are studied with the short-range system. Complementing these mid-frequency measurements is the use of nets to sample the fish and traditional high frequency acoustics for intercomparison with standard techniques (NOAA/NMFS).

The end results of the measurements are first-of-a-kind maps of distributions of swimbladder-bearing fish in two planes (vertical and horizontal) as derived from two broadband mid-frequency sonars at multiple scales. *What makes these results unique and powerful is that, not only are the data collected at high spatial resolution in these two orthogonal planes, but the data are also broadband and contain resonance information eliminating significant ambiguities in interpretation.* In addition, key parameters relevant to Navy signal processing systems of the echo statistics of the long-range sonar due to the patchiness are determined, allowing the development of physics-based bioclutter models and clutter-reduction methods.

Tim Stanton (WHOI) oversaw the entire program and was involved in every aspect, with an emphasis on the WHOI short-range downward-looking system. Cindy Sellers (WHOI) prepared for and participated in the cruises, as well as processed and analyzed data. Ben Jones (NPS) participated in data analysis and modeling. Mike Jech (NOAA/NMFS) conducted the biological sampling, performed high frequency acoustic surveys, and was involved in the design and execution of the cruises. Roger Gauss (NRL) led the NRL team (including Richard Menis, Ed Kunz, and Joe Fialkowski) involving use of their prototype mid-frequency broadband system for long-range detection and classification of fish.

WORK COMPLETED

The work involved conducting the September 2010 and 2011 cruises, processing, analyzing data from the two cruises, as well as submitting and publishing papers based on this and previous years' work. In addition, three students on this project (Ben Jones, Saurav Bhatia, and Wu-Jung Lee) received graduate degrees (Ph.D., M.S., and Ph.D., respectively). Illustrations of key results are in Figs. 1-20.

Published papers

a) The major manuscript that described the newly developed broadband methods and application of the new WHOI-Edgetech system at sea was published. The manuscript described the entire approach, including concept of the resonance classification system, choice of hardware, development of software, calibration procedures, field use, and interpreting data in terms of meaningful biological parameters (fish type, size, and numerical density) (Stanton et al., 2010). This was such an important milestone in the research, that a press release was published: http://www.whoi.edu/page.do?pid=7545&tid=282&cid=70786&ct=162. News and other media published stories based on this press release.

b) Data collected in this project were used by Stanton and Chu in another ONR grant (Undersea Signal Processing) to study the echo statistics associated with patches of fish in the resonance scattering region (2-4 kHz). A paper describing this analysis was published (Stanton and Chu, 2010).

c) Resonance classification to study mixed assemblages of fish. Here, major size classes of fish are spectrally resolved with our downward-looking broadband acoustic system and quantified in the case where traditional narrowband echosounders are inadequate. Understanding of predator-prey interactions was advanced through observations of co-located larger and smaller fish (Stanton et al., 2012).

d) Review of 30 years of advances in active bioacoustics. This article was invited as a means to help "kick off" the first issue of a new journal, Methods in Oceanography. (Stanton, 2012).

Submitted papers

a. Echo statistics from mixed assemblages (narrowband signals). This theoretical study formulates an exact expression of echo statistics from mixed assemblages of scatterers of varying sizes and numerical densities. This was inspired by the above resonance scattering study of mixed assemblages. The results are superior to those from the commonly used "mixture probability density function (PDF)" (Lee and Stanton, submitted).

b. Echo statistics from randomly oriented elongated scatterers. This theoretical study formulates expressions for echo statistics from randomly oriented prolate spheroids under various conditions—varying aspect ratio, with and without surface roughness, and with and without beampattern effects. This quantifies the degree to which the signals are non-Rayleigh for the various conditions and connects the physics of the scattering to parameters of the statistics. (Bhatia et al., submitted).

Dissertations

a. *"Echo statistics of aggregations of scatterers in a random waveguide: Application to biologic sonar clutter"* (Ben Jones, Ph.D., 2012). This was a two-pronged study that first modeled echo statistics due to various combinations of aggregations of scatterers (inspired by the fish application) for a long-range mid-frequency sonar and then applied the results to our Sept. 2011 cruise data. The cruise analysis not only involved the echo statistics, but also tied the spectral properties of the broadband echoes to the sizes and species of fish sampled in the area. The dissertation serves as the basis for two future journal articles, both of which are currently being prepared for submission.

b. *"Non-Rayleigh scattering by a randomly oriented elongated scatterer"* (Saurav Bhatia, M.S., 2012). This dissertation is based on the submitted paper described above. It contains a number of simulations beyond what is in the paper as well as software.

c. *"Broadband and statistical characterization of echoes from random scatterers: Application to acoustic scattering by marine organisms"* (Wu-Jung Lee, Ph.D., 2013). This was a multi-pronged study on scattering and associated echo statistics from individuals (squid) and mixed assemblages of scatterers, using both narrowband and broadband signals. An order of magnitude improvement was made in parameter estimation using these new approaches.

Drafted manuscript

In a new effort started this year, statistics of broadband direct-path echoes from assemblages of scatterers have been studied. Both development of theory and comparison with our ocean data were conducted in this latter case and a manuscript has been drafted. This manuscript was based on chapter 4 of Wu-Jung Lee's Ph.D. thesis (Lee, 2013).

RESULTS

We have demonstrated that at long ranges and mid frequencies (1-9 kHz), echoes from aggregations of fish can dominate other sources of reverberation in this coastal region, and moreover that the spatial characteristics of fish and their echo statistics are specific to geographical region (Jeffreys Ledge: dispersed; Franklin Swell: compact/sparse; and Georges Bank: shoals/large aggregations). We have further demonstrated that we can classify both the short-range and long-range data in terms of the resonances associated with the presence of the various sizes and species of swimbladder-bearing fish. Our statistical analyses of echoes, both theoretical and experimental, have quantified the connections between biologically meaningful properties and parameters, associated scattering physics, and parameters of the statistical distributions. The degree to which the echoes are non-Rayleigh is a complex function of sonar system parameters (e.g., the source and receiver beampatterns), scatterer type (such as size and shape) and scattering geometry (including waveguide effects and spatial distribution of scatterers).

IMPACT/APPLICATIONS

Our complementary sets of high-resolution short- and long-range broadband (1-9 kHz) data are a first of a kind and are revealing important information on the behavior of fish. The advanced broadband approach provides new insight into biological processes over conventional approaches: a) both broadband systems are well suited for determining fish size through resonance classification (conventional narrowband acoustic systems cannot determine size); and b) the long-range sonar is well suited for rapidly and synoptically sampling sparsely-distributed dense compact aggregations of fish (conventional systems grossly under-sample sparse distributions). This approach of using broadband sound in two planes (vertical and horizontal) sets a new high standard by which acoustic measurements should be made in order to characterize distinct classes of fish.

The scientific benefits include new insights into: a) predator-prey relationships (from resonance classification of multi-size fish assemblages); and b) region-specific behavior of fish (from spatial mapping).

The Navy benefits include new information on quantifying both the regional variability of bioclutter and the clutter characteristics that, in turn, can be used to enhance ASW sonar performance (see "Transitions").

TRANSITIONS

We have completed one transition and are currently scheduled for our second transition of our work (Fig. 21). Completed: Advanced Capability Build 13 (ACB 13) of the Surface Ship ASW Synthetic Trainer (SAST) (PEO IWS 5A). Near completion: Common Acoustic Simulation Environment

(CASE) trainer for air-deployed ASW sonars. Both of these transitions are based on results from our work on our pilot cruise that preceded this project and via a sequence of the ONR Undersea Signal Processing D&I program (Keith Davidson) and the High Fidelity Active Sonar Training (HiFAST) FNC program (Mike Vaccaro) and in collaboration with Dr. Brian La Cour of ARL:UT and LCDR Ben Jones of NPS. Below is a summary of the sequence for both transitions:

1) The statistical properties of mid-frequency echoes from fish were measured in our pilot cruise in 2005. In that cruise, the patchiness of the fish was observed at high resolution through towing our system (funded by ONR DURIP) deep and just over the patches of fish. The data spanned several important geometries—sonar beam within a patch, sonar beam sweeping across one patch edge, and sonar beam sweeping across multiple patches.

2) The data described in #1 above served as the basis for developed analytical descriptions of the sonar echo statistics in the ONR Undersea Signal Processing program. Models were developed appropriate for each scattering geometry. Furthermore, a general echo statistics model was developed, inspired by this first analysis.

3) In the HiFAST program, we modeled the clutter due to patches of fish. Part of the analysis involved use of the scattering models that we applied in analyzing the data in this current (ONR Biology) program. Hence the models were grounded with scientific data (which included net samples provided by NOAA/NMFS). Furthermore, via simplifying assumptions in the modeling, computation time was reduced (essential for synthetic trainers). The fidelity of these simplified models was tested, in part, through use of the new statistics models that we developed in #2 above.

RELATED PROJECTS

1. Stanton has been funded through the Undersea Signal Processing Division of ONR to study the statistics of the fish echoes (sequence of D&I grants N00014-07-1-0232 and N00014-09-0428). The data from this (Biology) program have been used as a basis for studying echo statistics of mid-frequency echoes due to the presence of fish (Stanton and Chu, 2010) as well as to inspire development of new advanced theoretical formulations for echo statistics. **2.** Stanton was also funded through the Undersea Signal Processing Division of ONR to study statistics of echoes from elongated objects (D&I grant N00014-11-1-0116). The results in that project are general and apply to fish in this (Biology) program. **3.** Under the HiFAST FNC program of ONR (grant N00014-11-1-0241; Mike Vaccaro), Stanton has collaborated with Drs. Brian LaCour of ARL:UT and LCDR Ben Jones of NPS to *transition* the new knowledge that originated in this project to the ACB13 SAST system. Another transition is scheduled for the CASE (see above in "Transitions"). Other Navy systems are targeted for future transitions. **4.** Commencing in FY10, Stanton and Gauss participated on a PEO C4I & Space (PMW 120; Marcus Speckhahn) panel to help develop a phenomenological approach that can nowcast/forecast spatial distributions of biologics for mid-frequency ASW applications based on oceanographic, biologic, and acoustic data and models. **5.** Gauss is also on the ONR 322OA (Robert Headrick) Applied Reverberation Modeling Board (ARM-B) whose charter is to understand the limitations/major challenges presented by today's and tomorrow's active sonars relative to reverberation and clutter predictive capabilities, and recommend solutions (the way ahead). Its initial focus is on mid-frequency active monostatic sonars. Both #4 and 5 allow Stanton and Gauss to identify and act on technology insertion points. **6.** Gauss is currently funded by PMW-120 to use archival fish information (the literature and high-fidelity acoustic data) to: a) establish the viability and procedures

for systematically estimating volume scattering strength (VSS) (via NRL's Fish Scattering Strength (FSS) algorithm); and b) transition these statistical estimates to the VSS Database in CNMOC's Oceanographic and Atmospheric Master Library (OAML), the repository of Navy-standard algorithms, databases, and models. The planned Stanton enhancements to his scattering formulations could serve as a basis of FSS upgrades. **7.** Gauss has been developing moment-based clutter-rejection techniques for improving automated active Navy classifiers that will be under evaluation for transition to the ACB AN/SQQ-89 A(V) 15 system (ACB-17) in FY12-14 under the ONR Active Sonar Automation Enabling Capability Project (Keith Davidson). **8.** Gauss is also collaborating with NUWC (Wendy Petersen—2010 cruise participant—and Jenna McKown) in determining the potential impact of bioclutter on Navy automated trackers, and the ability of moment-based methods to characterize and control false tracks due to bioblutter.

PUBLICATIONS

Refereed journals

Stanton, T.K. and D. Chu (2010) "Non-Rayleigh echoes from resolved individuals and patches of resonant fish at 2-4 kHz," *IEEE J. Ocean. Eng.*, **35**: 152-163. [refereed]

Stanton, T.K., D. Chu, J.M. Jech, and J.D. Irish (2010) "New broadband methods for resonance classification and high-resolution imagery of fish with swimbladders using a modified commercial broadband echosounder," *ICES J. Mar. Sci.*, **67**: 365-378. [refereed]

Stanton, T.K., C. Sellers, and J.M. Jech (2012) "Resonance classification of mixed assemblages of fish with swimbladders using a broadband echosounder at 1-6 kHz," *Can. J. Fish Aq. Sci.* **69**: 854-868. [published, refereed]

Stanton, T.K. (2012) "30 years of advances in active bioacoustics: *A personal perspective,"* Methods in Oceanography, doi:10.1016/j.mio.2012.07.002. (Invited review article). [refereed]

Lee, W.-J. and T.K. Stanton (submitted) "Statistics of echoes from mixed assemblages of scatterers with different scattering amplitudes and numerical densities," submitted to IEEE J. Ocean. Eng. [submitted, refereed]

Bhatia, S., T.K. Stanton, and K. Baik (submitted) "Non-Rayleigh scattering by a randomly oriented elongated scatterer randomly located in a beam," submitted to IEEE J. Ocean. Eng. [submitted, refereed]

Dissertations

Jones, B. A. (2012) "Echo statistics of aggregations of scatterers in a random waveguide: Application to biologic sonar clutter", Ph.D. dissertation, Naval Postgraduate School. [published]

Bhatia, S. (2012) "Non-Rayleigh scattering by a randomly oriented elongated scatterer", M.S. thesis, MIT/WHOI. [published]

Lee, W.-J. (2013). "Broadband and statistical characterization of echoes from random scatterers: Application to acoustic scattering by marine organisms," Ph.D. thesis [published]

Regions of study

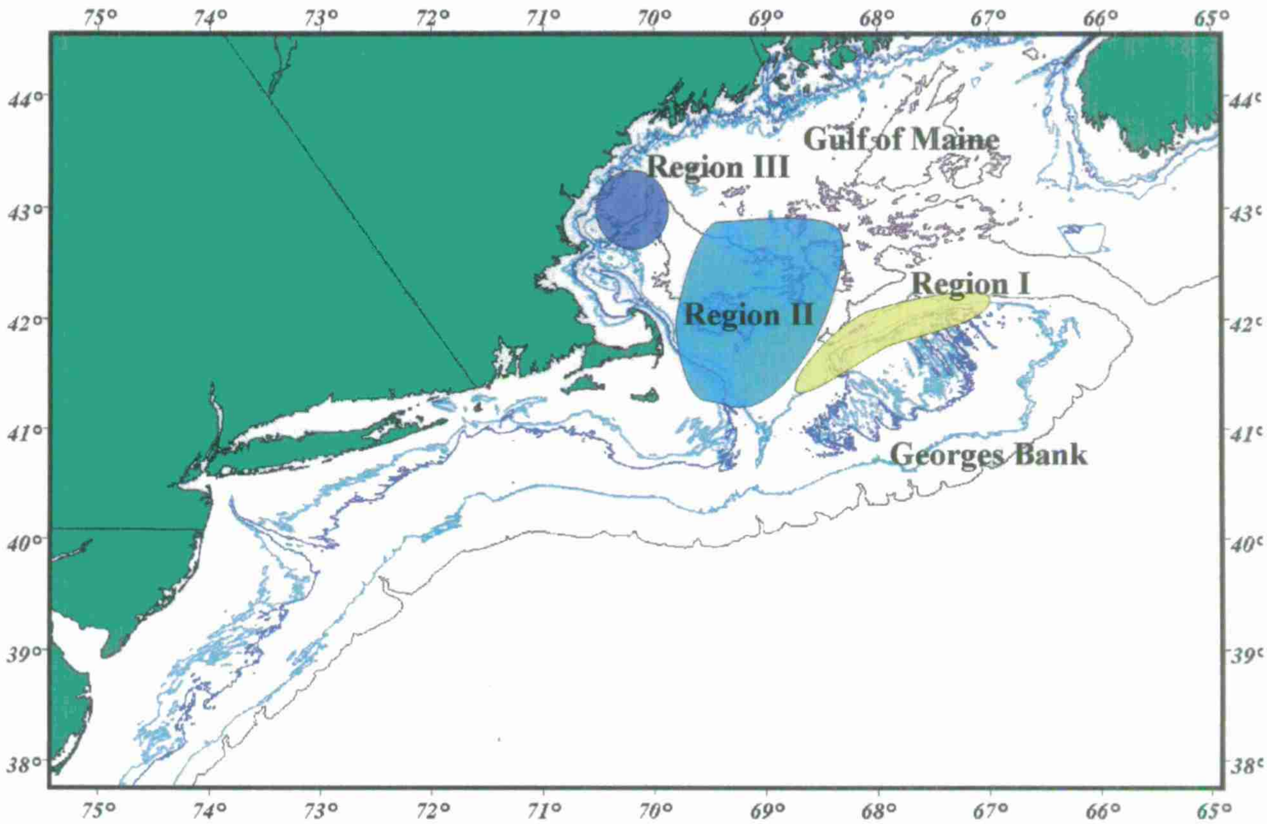


Figure 1. The cruises focused on Regions I and II, and, to some extent, Region III. Region I involves a section of Georges Bank, Region II includes Franklin Swell, and Region III includes Jeffrey's Ledge. The three regions were chosen as they represent varying degrees of complexity in species composition. The pelagic species in Region I are dominated by Atlantic herring during the fall. Although herring will frequently dominate the composition of aggregations of fish, there will also be mixes of species including silver hake, red hake, butterfish, redfish, and pearlsides, all of which contain swimbladders.

Two dual-ship experiments

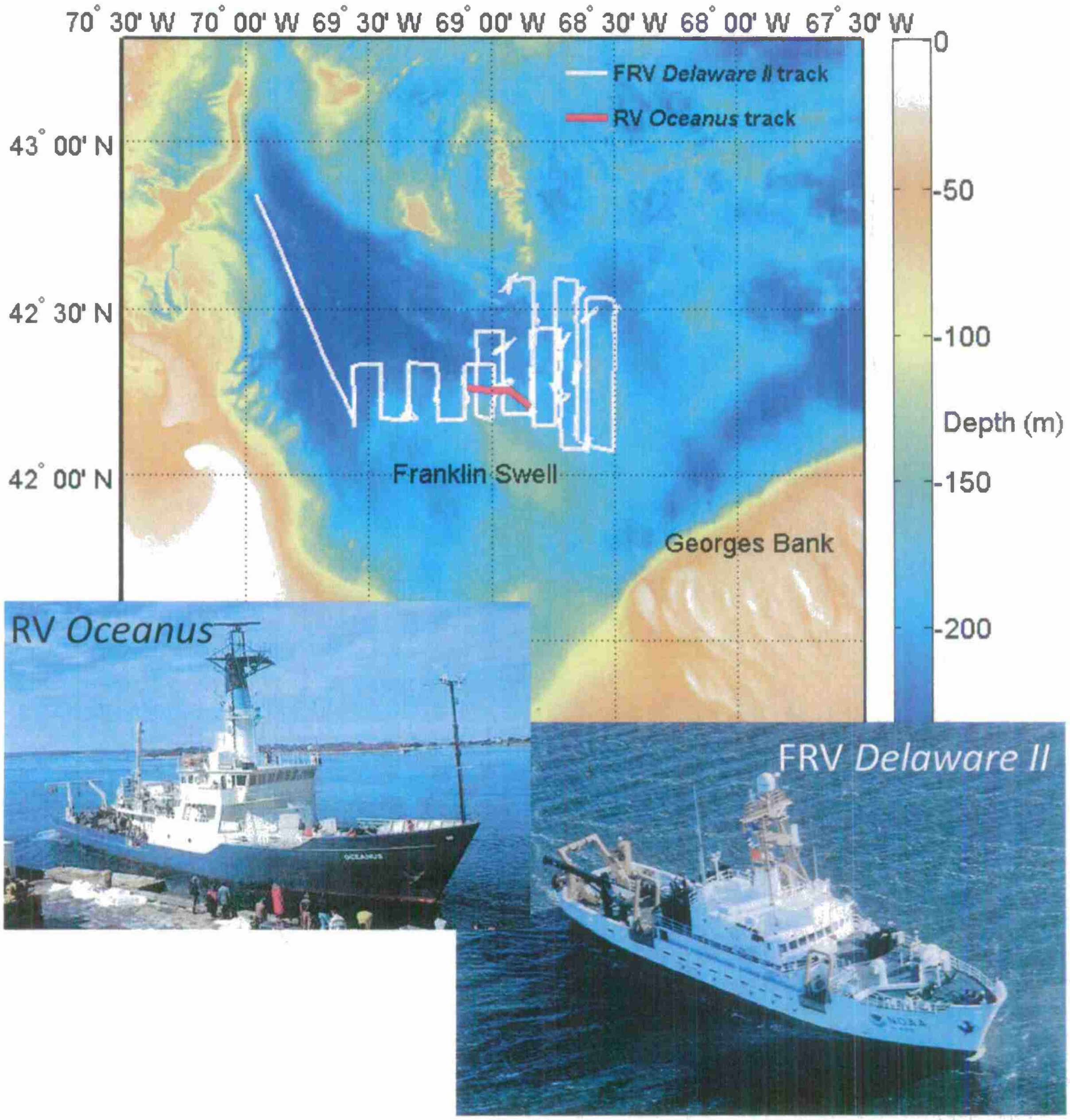


Figure 2. Each year involved use of both a UNOLS and NOAA Fisheries ship. Illustrated is the dual-ship experiment in the Gulf of Maine in September 2011. The ship tracks shown in the top image correspond to the Franklin Swell component of the experiment (Region II in Fig. 1) (adapted from Jones, 2012).

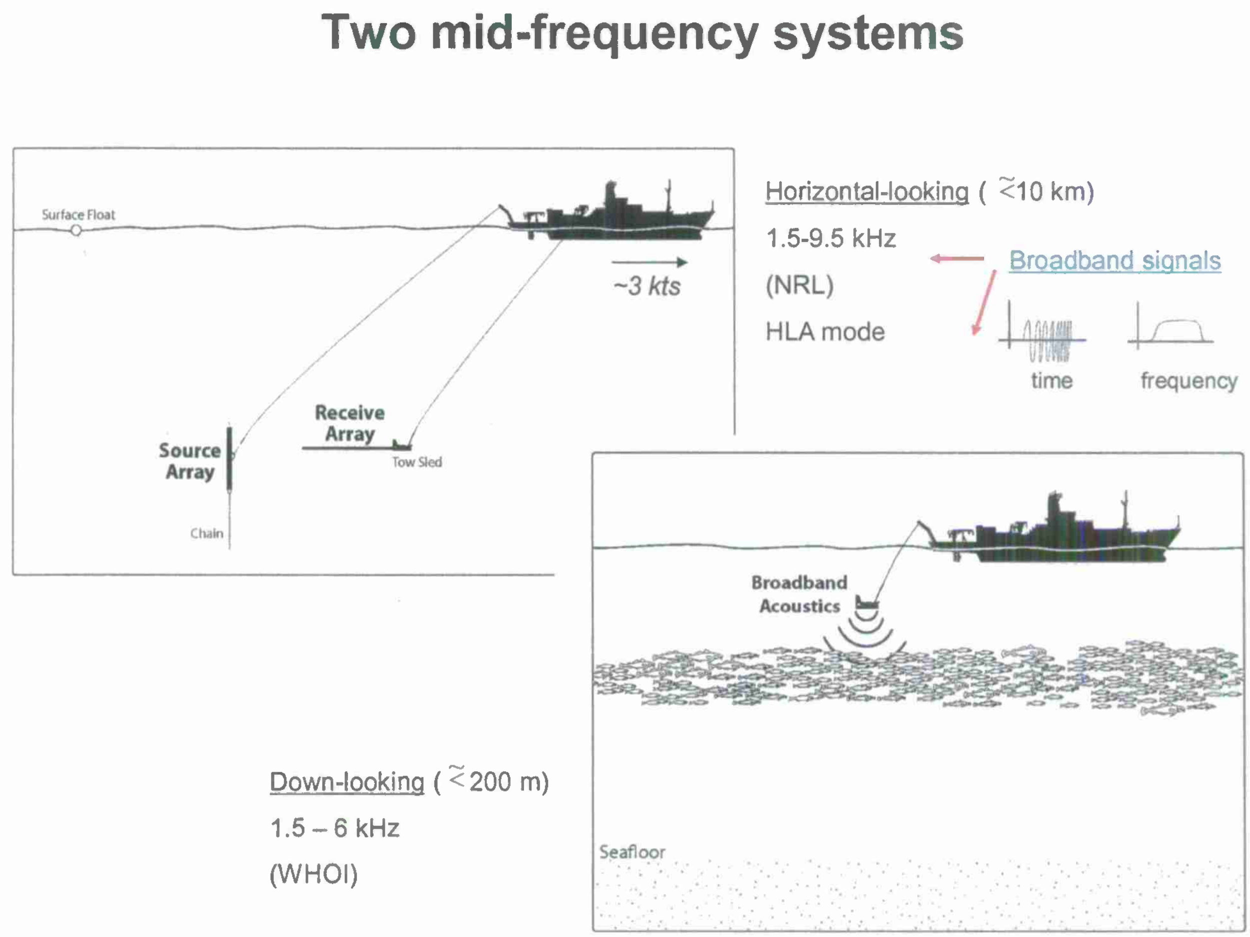
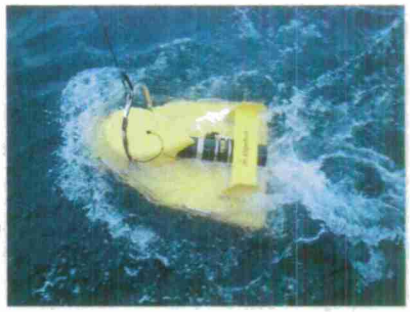
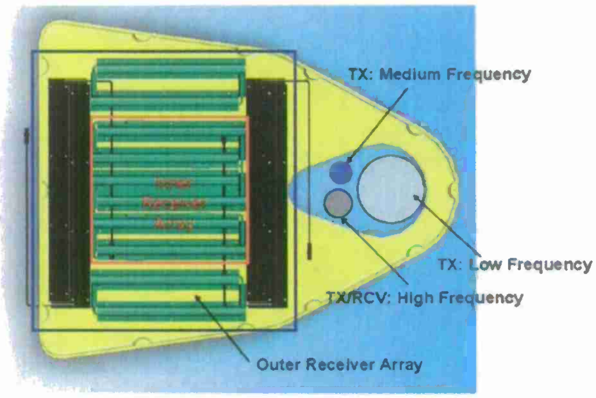


Figure 3. Deployment configuration for the two broadband mid-frequency active acoustic systems. The two systems were deployed in sequence from the same UNOLS vessel.

WHOI down-looking, modified-echosounder system



Underside of Towbody



4-Channel System

1.5-6 kHz
4-20 kHz
30-70 kHz
50-110 kHz

Figure 4. Broadband active acoustics system used for short-range downward-looking detection of fish.

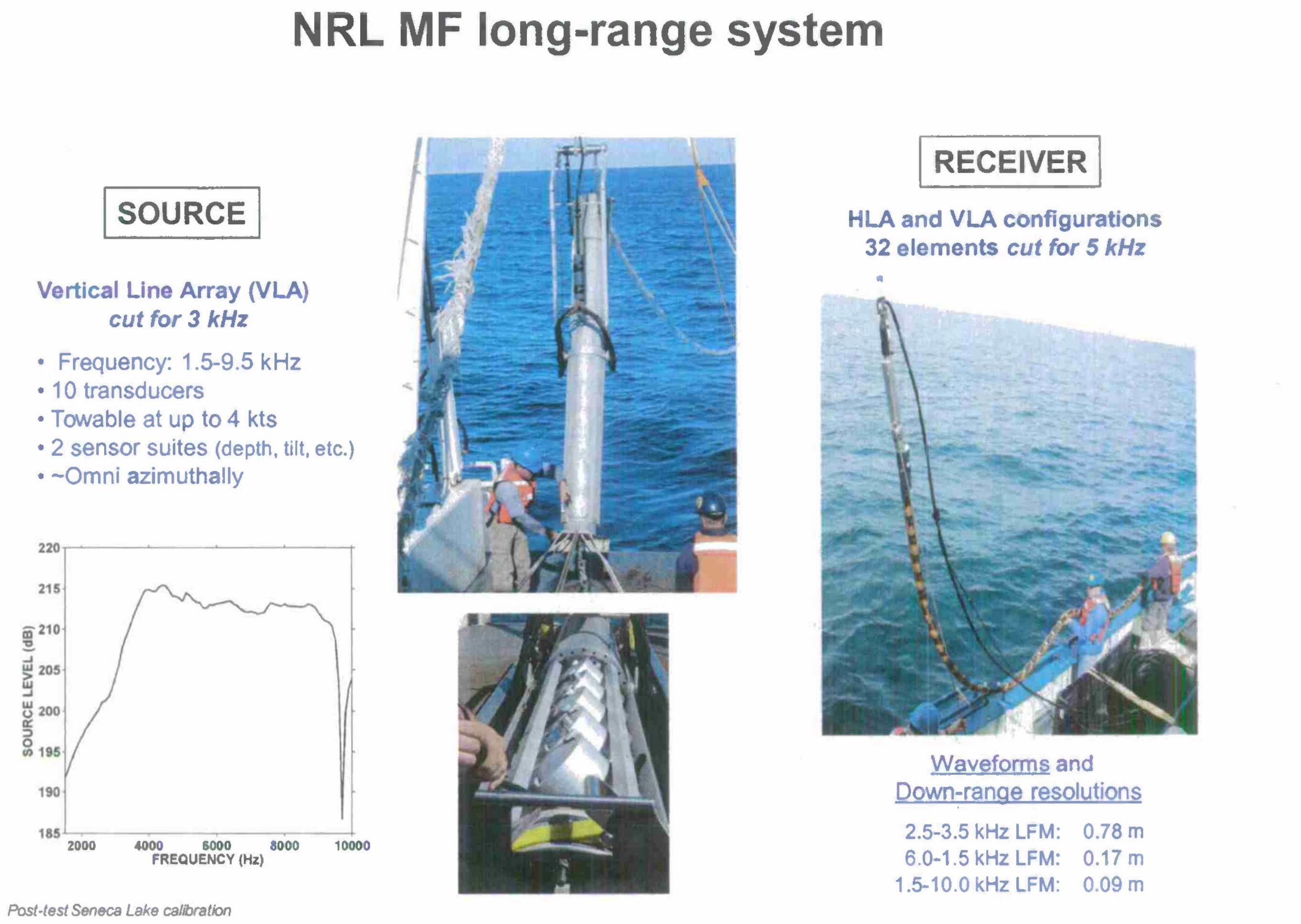


Figure 5. Broadband active acoustics system used for long-range horizontal-looking detection of fish.

NOAA-Fisheries trawl

Figure 6. Pelagic trawl, provided by the National Marine Fisheries Service, streaming out behind the ship before being lowered down to depth.

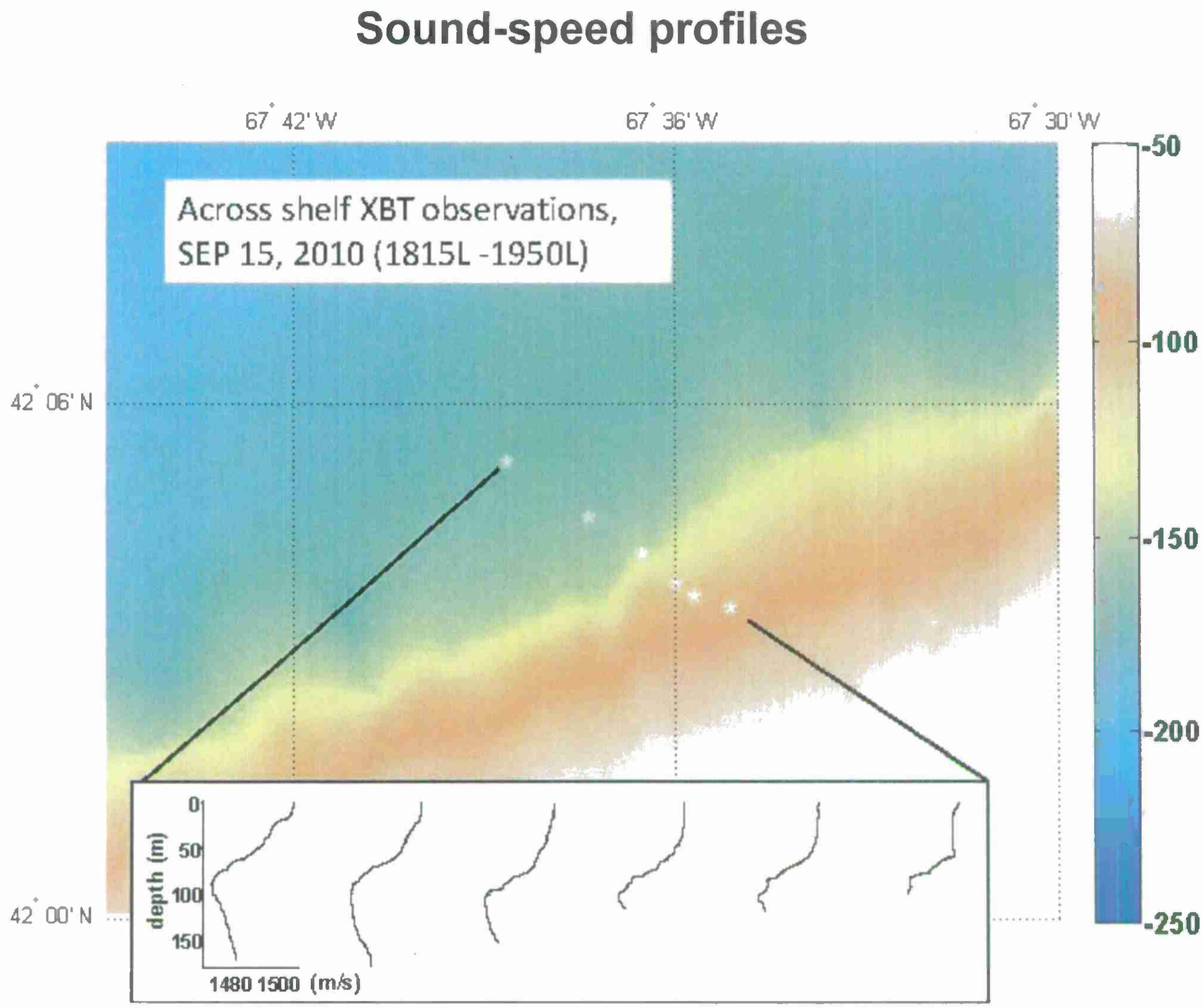


Figure 7. Sound speed profiles collected along the gradient of depth. The variability with location demonstrates the need to account for a range-dependent waveguide in interpreting the echoes from the long-range sonar.

2010 experiment: Results overview

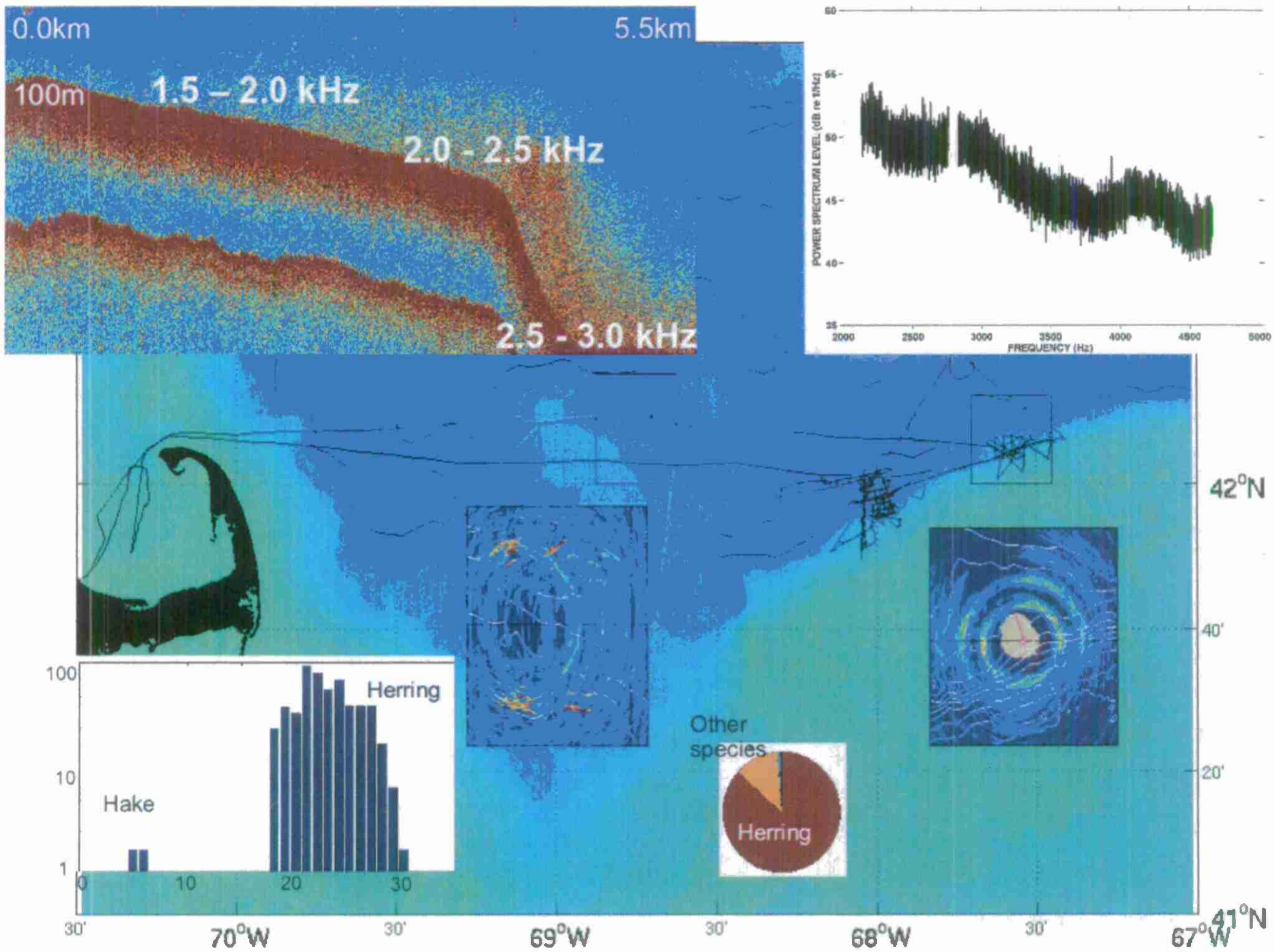


Figure 8. Synthesis of data collected in two regions, Franklin Swell (left black box) and Georges Bank (right black box). Polar plots of data from NRL long-range sonar in those areas are given directly below the corresponding boxes. Upper left panel: 1-6 kHz echogram from WHOI downward-looking system, with range of resonances given in white numbers. Upper right panel: Spectrum of data from NRL system from Georges Bank. Lower left panel and pie chart: net samples from Georges Bank.

Down-looking sonar (1-6 kHz): Shoals of fish at edge of Georges Bank (2010)

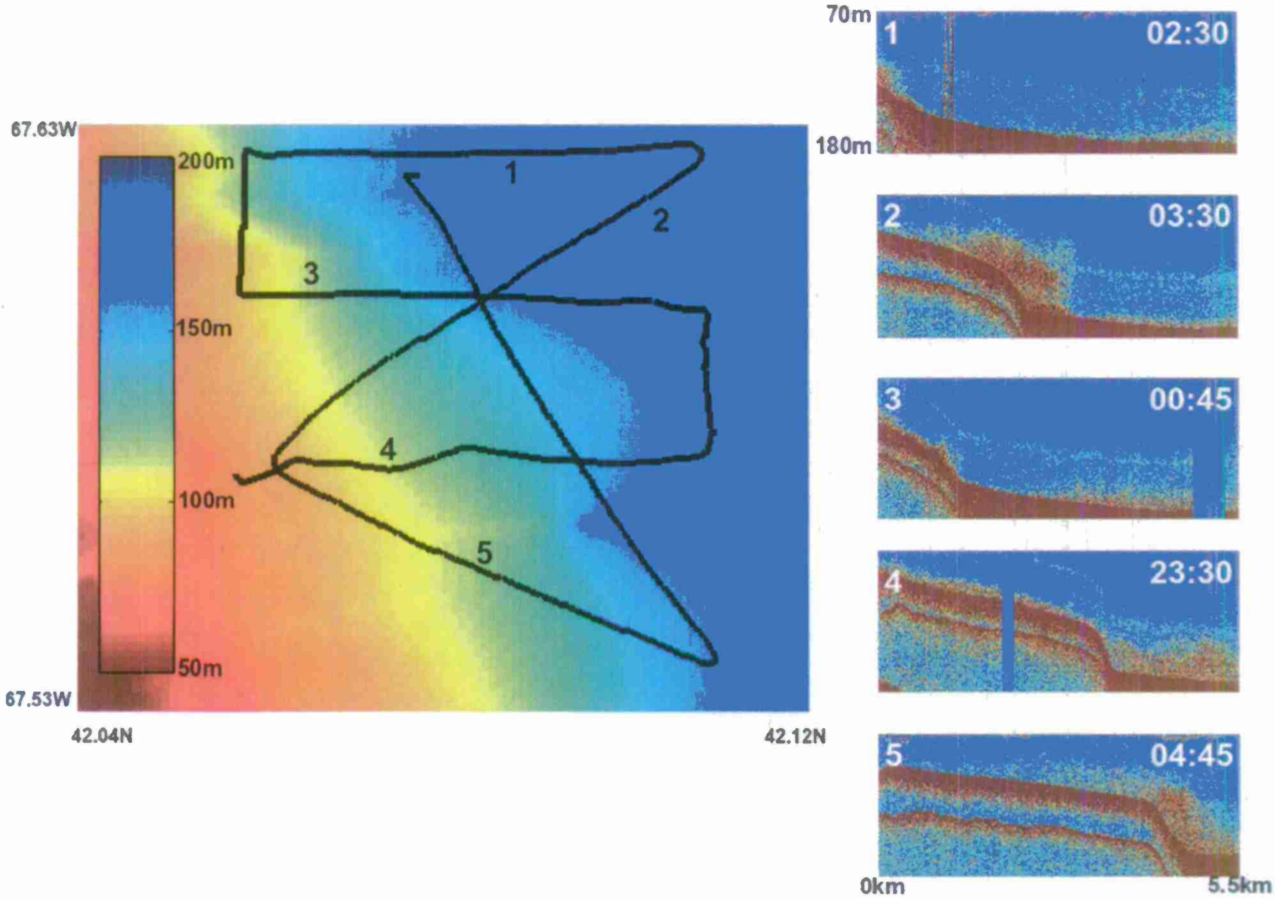


Figure 9. Left: transects of WHOI downward-looking system studying one area of Georges Bank. Right: echograms from WHOI system for each of the track lines, illustrating the spatial variability—along-bank and cross-bank—of the herring. A resonance analysis of one of the track lines is given in the upper left panel of Fig. 8.

Long-range sonar: Shoals of fish at Georges Bank (2010)

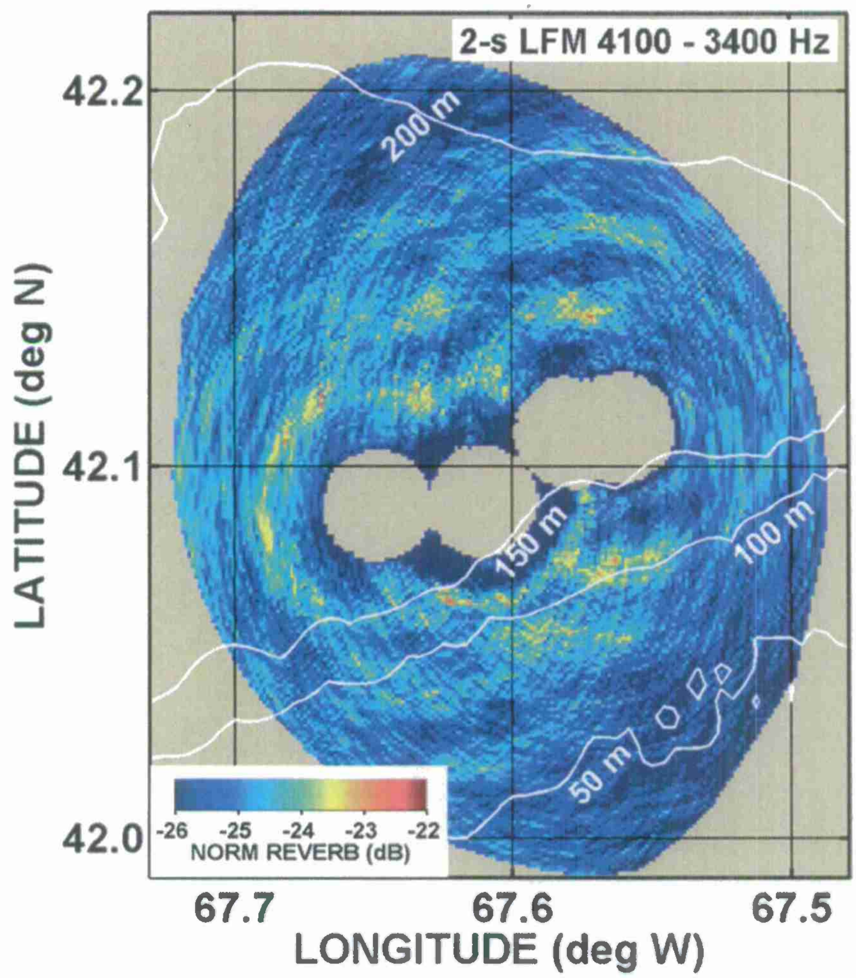


Figure 10. Georeferenced echoes from an average of four pings at distinct location and bearings collected with the long-range sonar on the northern flank of Georges Bank. The averaging serves to reduce or eliminate left-right ambiguity of the receive line array. The banding is due to convergence zone effects. All data are matched filtered and energy normalized.

Long-range sonar: Shoals vs. compact patches (2010)

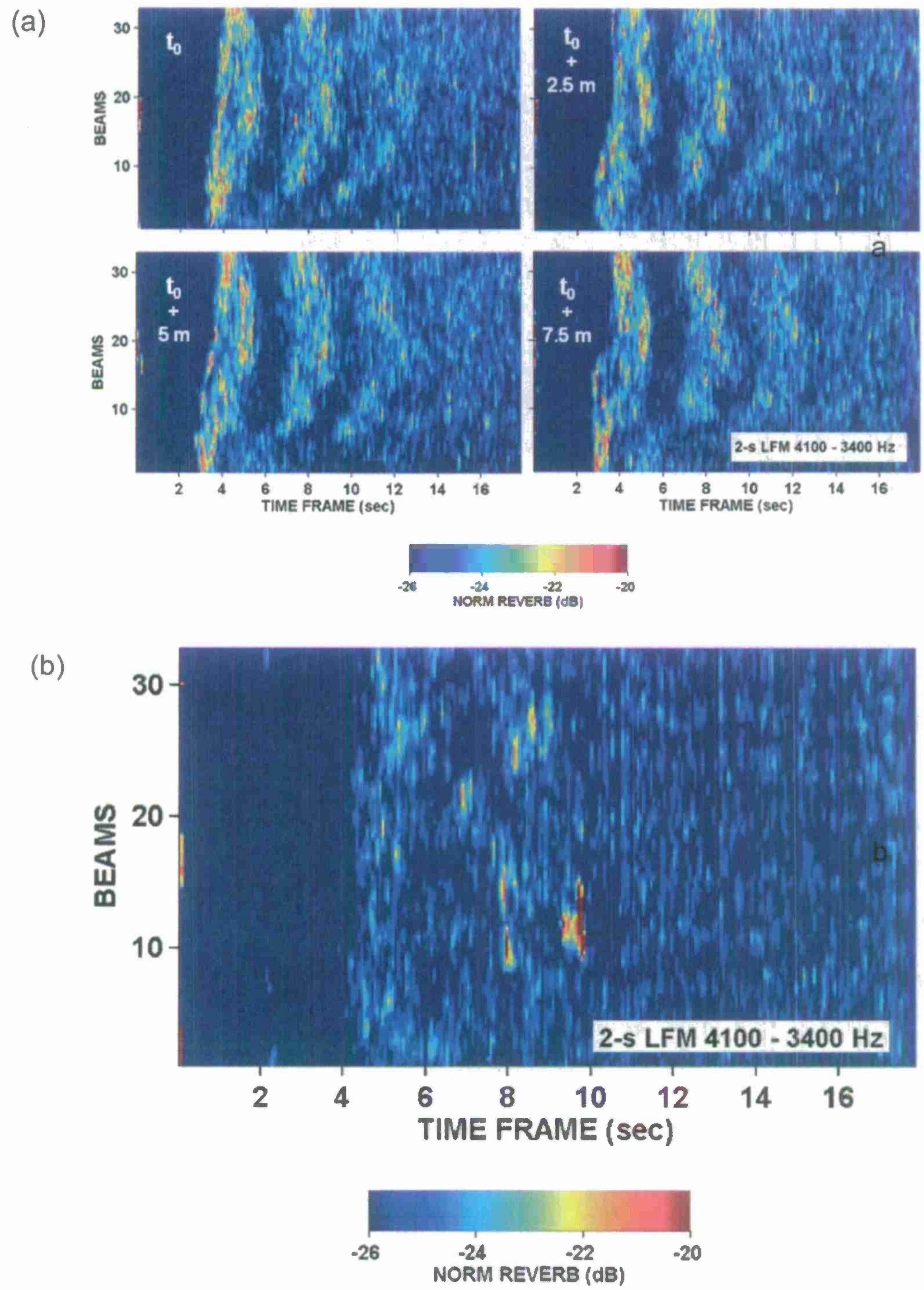


Figure 11. Long-range broadband echoes from patches of fish in two regions: a) Georges Bank and b) Franklin swell. This illustrates the significant change in patch structure between the two regions—shoals and sparse compact patches, respectively. The banded structure in (a) is due to convergence zone effects. All data are matched filtered and energy normalized.

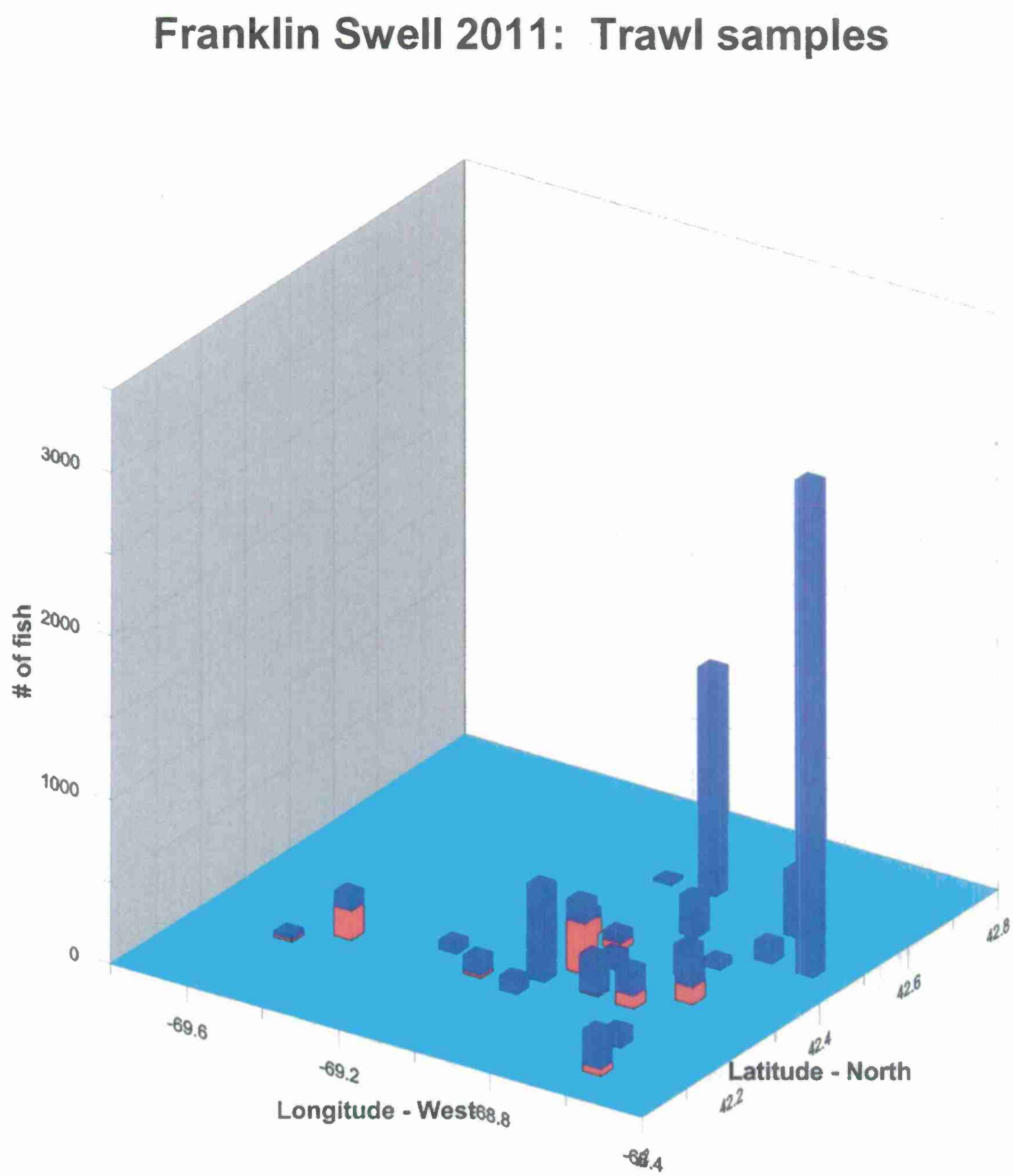


Figure 12. Each column represents one mid-water trawl location in the Franklin Swell area. Blue: Atlantic herring (*Clupea harengus*). Red: Acadian redfish (*Sebastes fasciatus*).

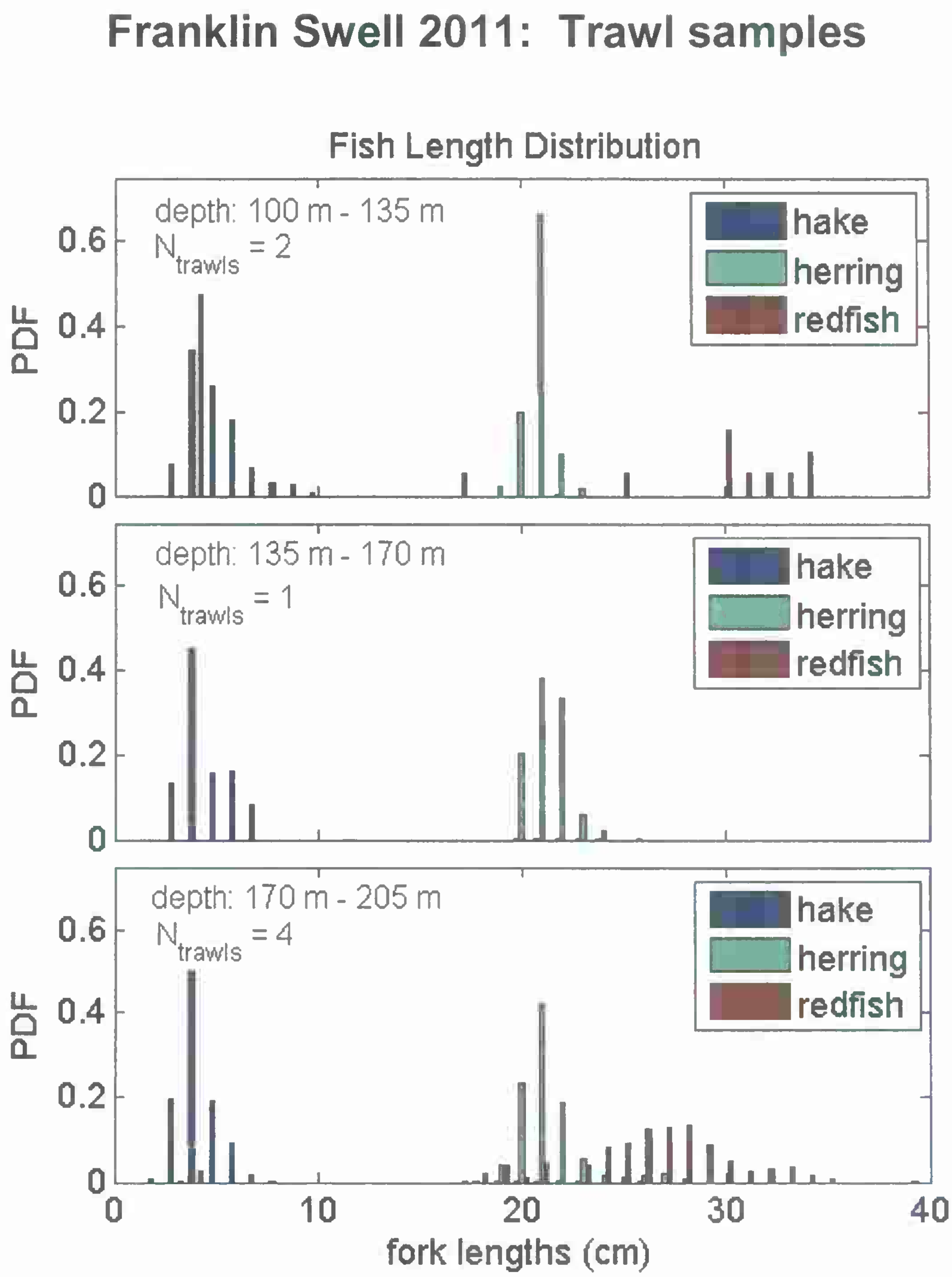


Figure 13. Samples of fish collected by NOAA Fisheries from the Franklin Swell area in 2011 (adapted from Jones, 2012).

Franklin Swell 2011
Long-range acoustic echoes from fish schools

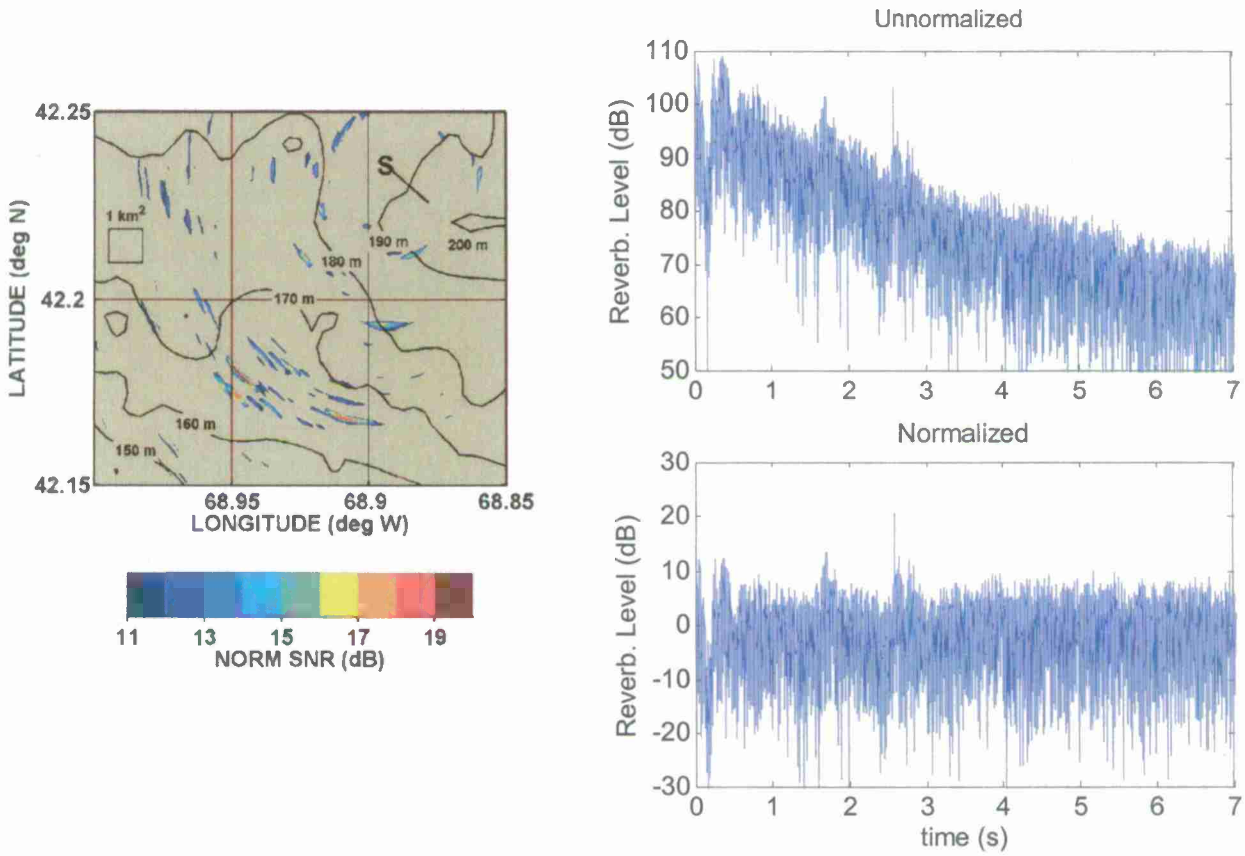


Figure 14. Matched filter output of long-range sonar echoes from fish in the Franklin Swell area in 2011: (left) georeferenced normalized echoes superimposed with bathymetric contours; and (right) normalized (bottom) and unnormalized (top) echoes for one look direction (beam 27). (Adapted from Jones, 2012.)

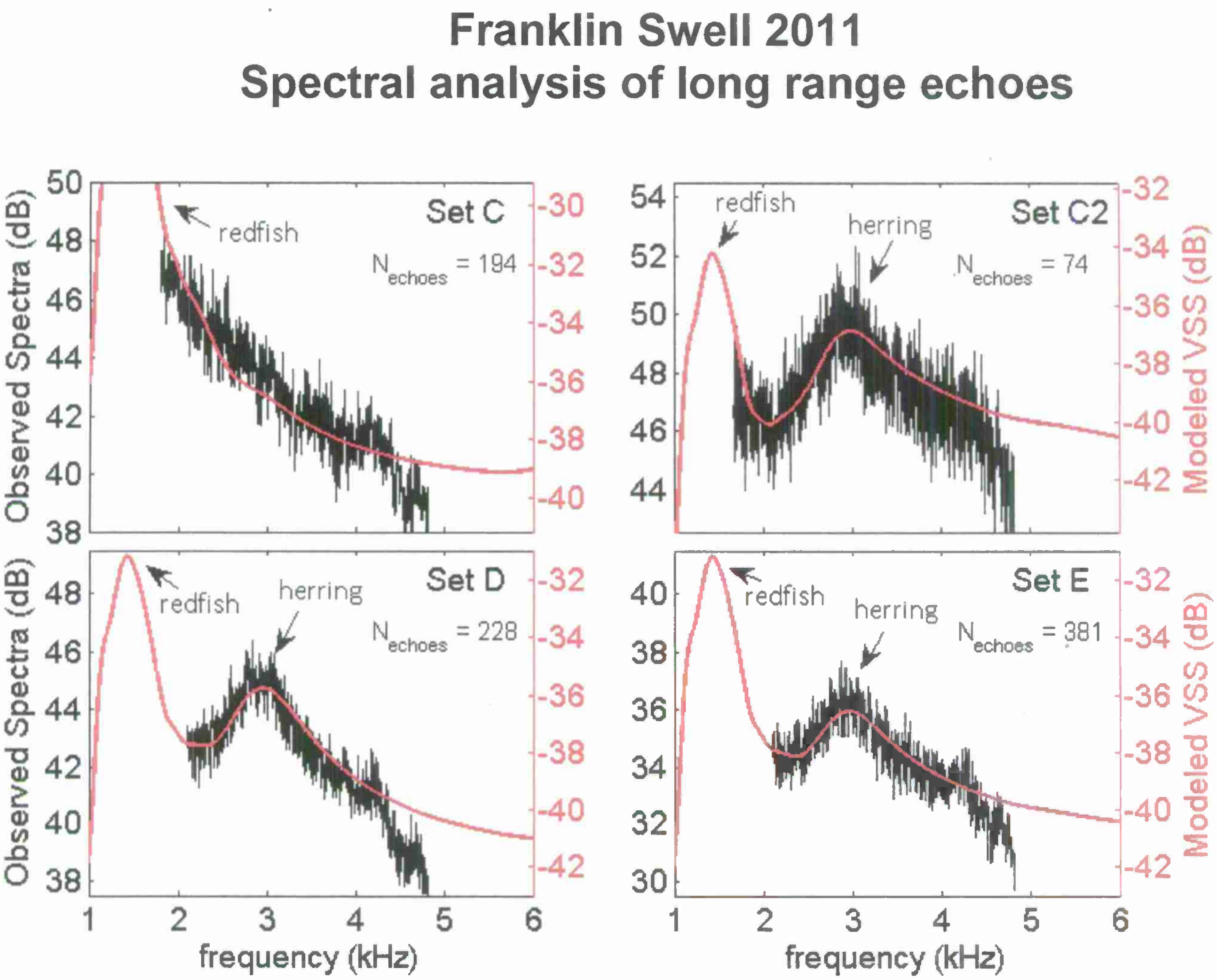


Figure 15. Spectra of observed and modeled mid-frequency echoes from two species of fish from the Franklin Swell area in 2011 (adapted from Jones, 2012).

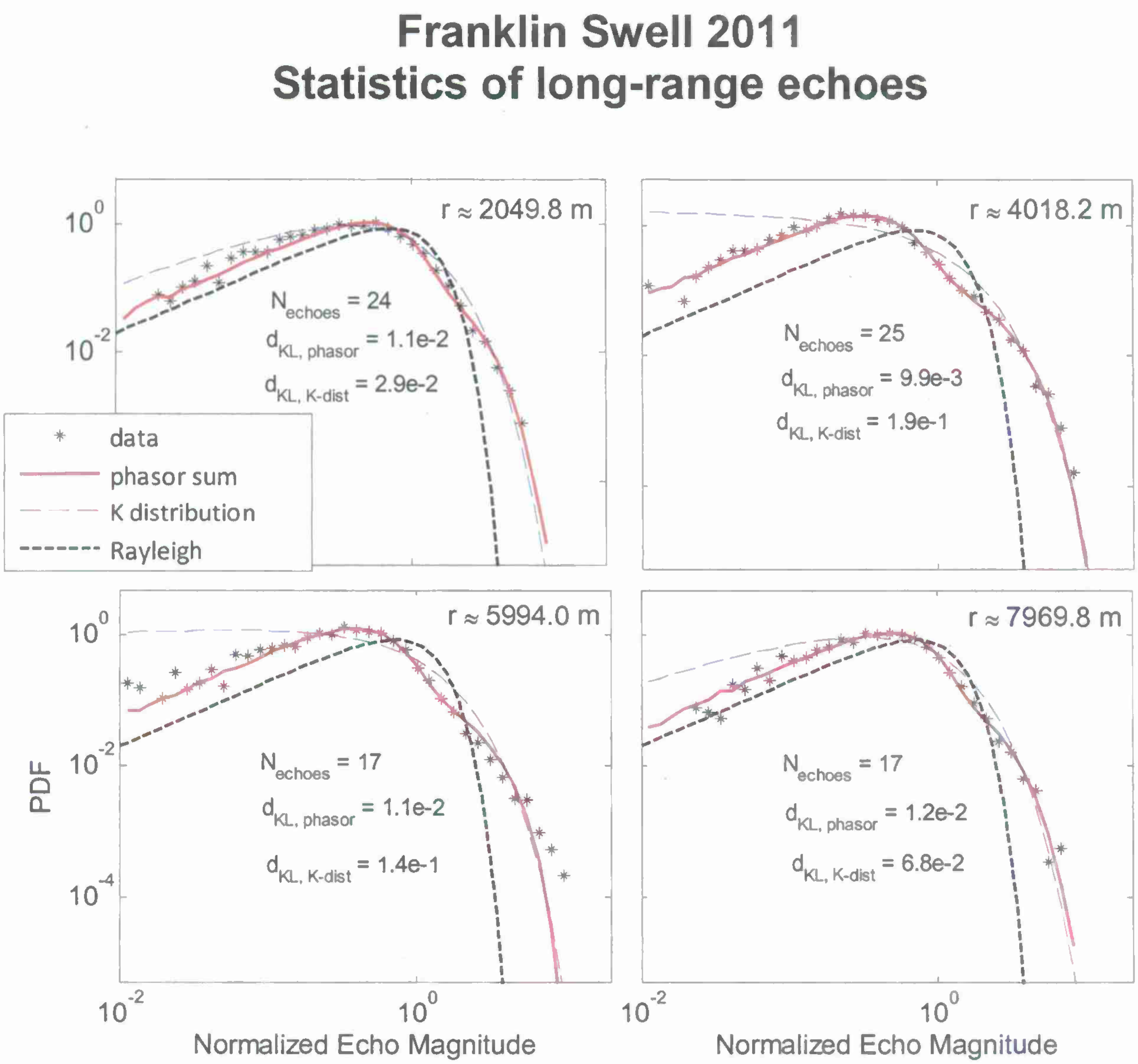


Figure 16. Statistics of long-range mid-frequency echoes from fish at various ranges in the Franklin Swell area in 2011. The degree to which the echoes are non-Rayleigh is illustrated, as well as comparison with two models. (Adapted from Jones, 2012.)

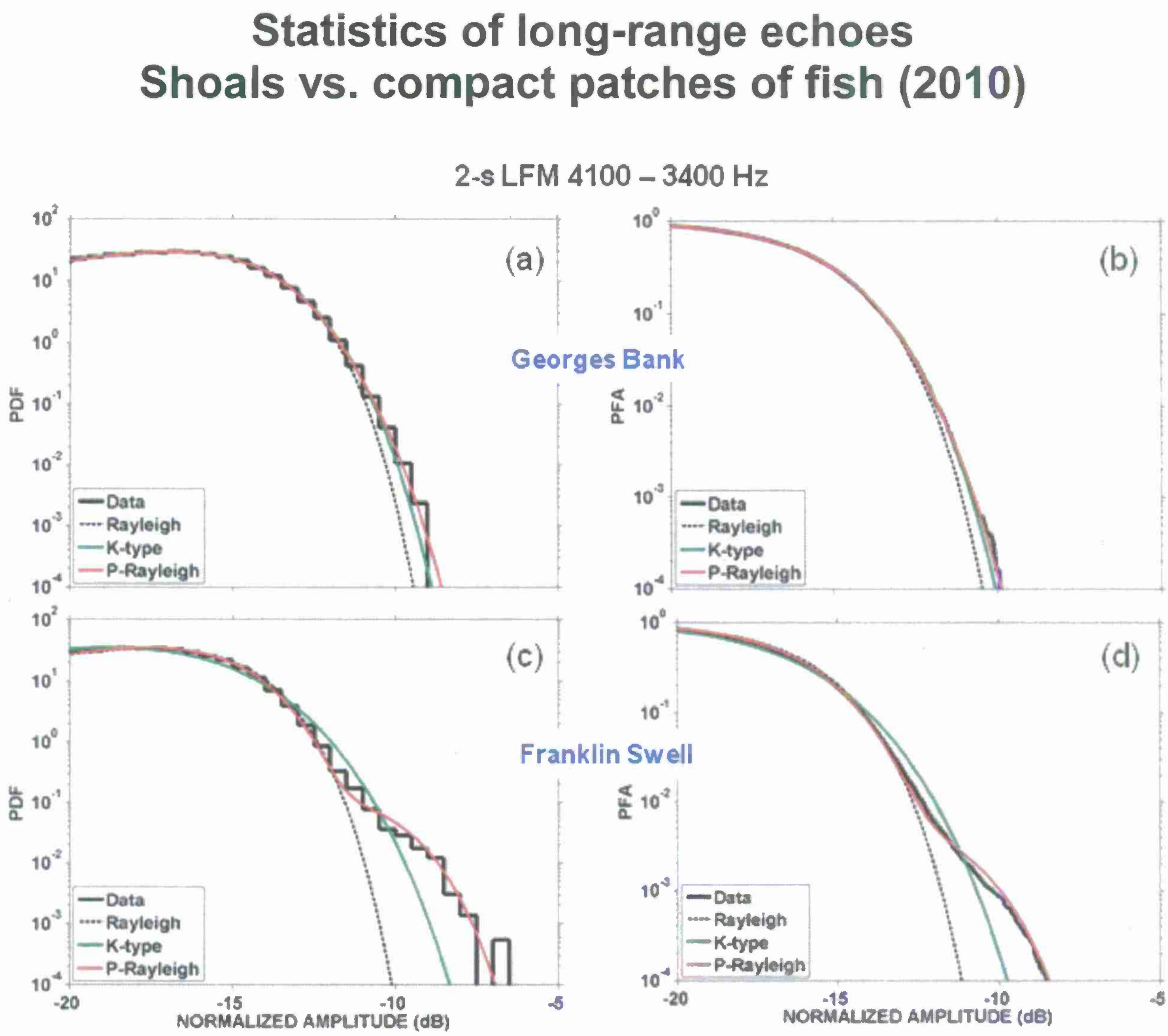


Figure 17. Echo statistics from two regions as collected with the long-range sonar in 2010—Georges Bank (upper row) and Franklin Swell (lower row). Probability Density Function (PDF) is given in the left column and Probability of False Alarm (PFA) is given in the right column. The significantly raised tail from the Franklin Swell area is due to the sparse compact nature of the patches of fish.

Franklin Swell 2011: Individual fish at 1-6 kHz

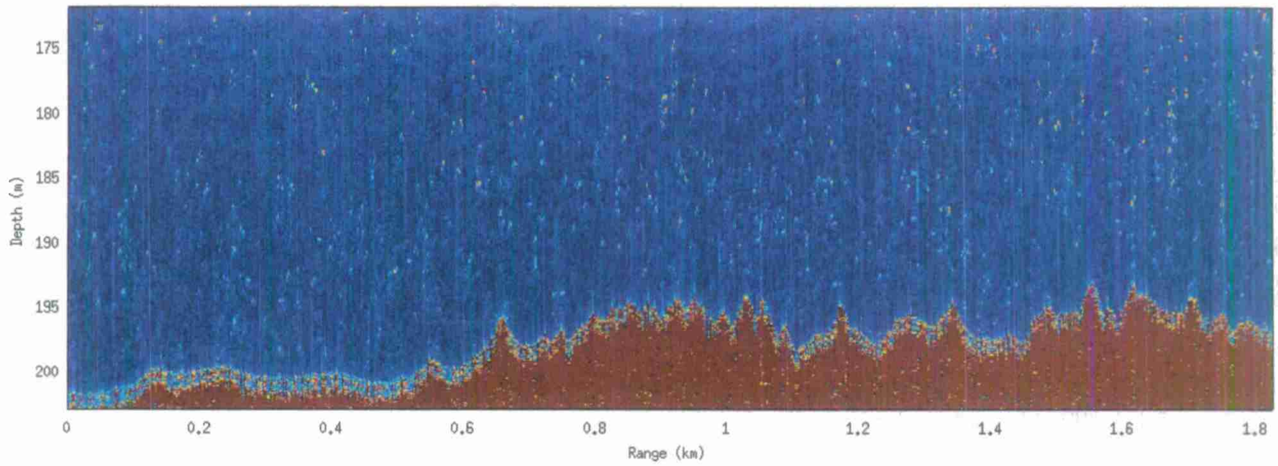


Figure 18. Echoes from individual fish in a miles-long shoal as measured with the WHOI downward-looking system. The system was towed deep and just above the shoal so as to resolve the individuals and increase the signal-to-noise ratio.

Franklin Swell 2011: Dense fish aggregations on seafloor

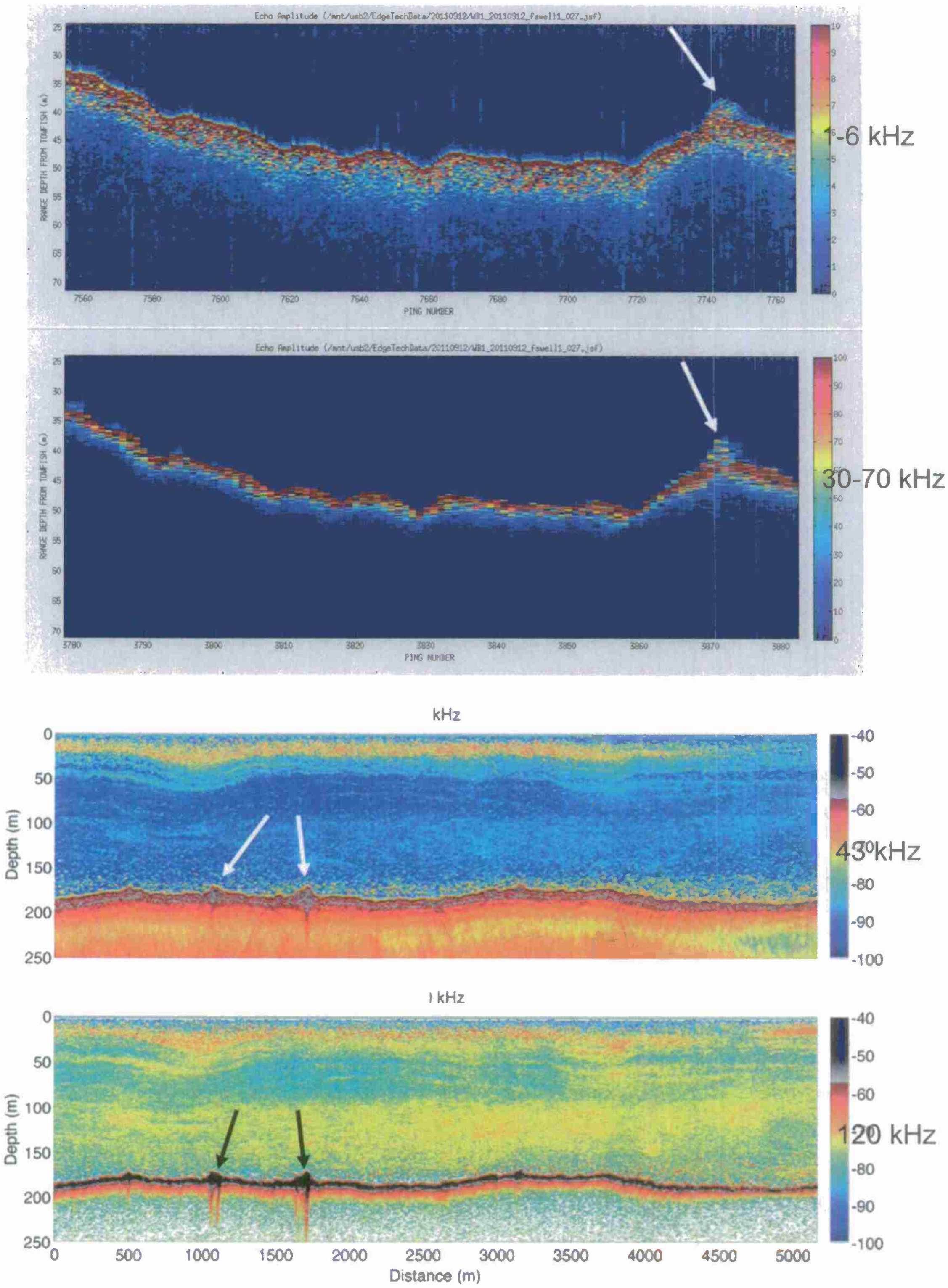


Figure 19. Observations of 100-m-long dense patches of fish on the seafloor. The streaks below the 120 kHz data (bottom panel) suggest second-order scattering.

Georges Bank 2008: 30-70 kHz channel

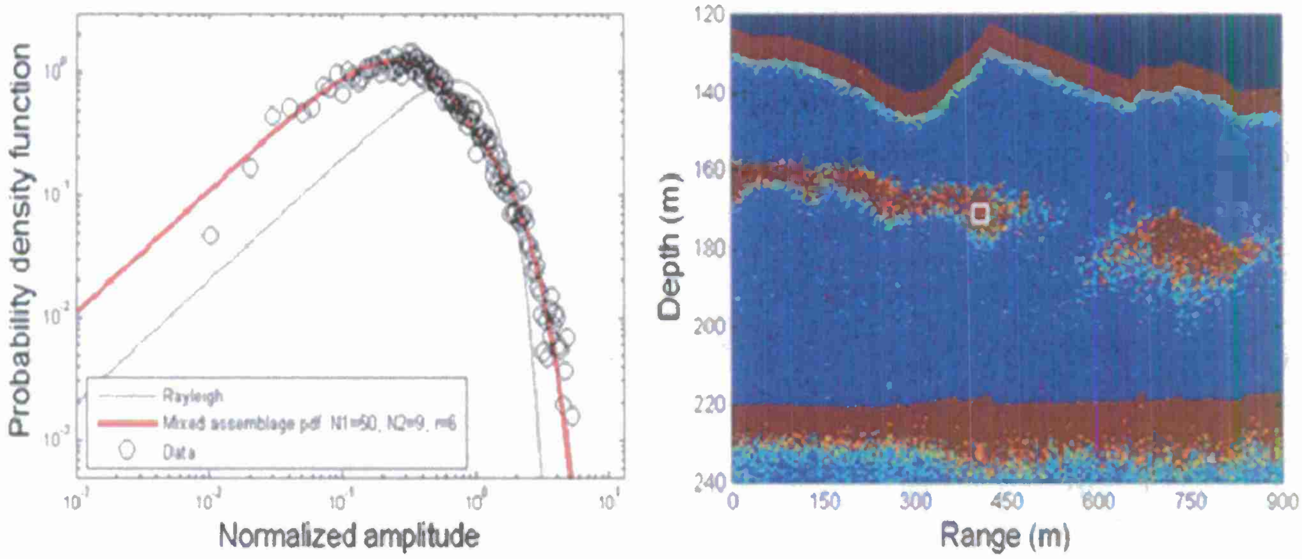


Figure 20. Statistics of echoes from mixed assemblages of fish. Left: our newly developed analytical model for echo probability density function (PDF) is compared with data. Right: echogram of fish patch. The white box is the sample window analyzed.

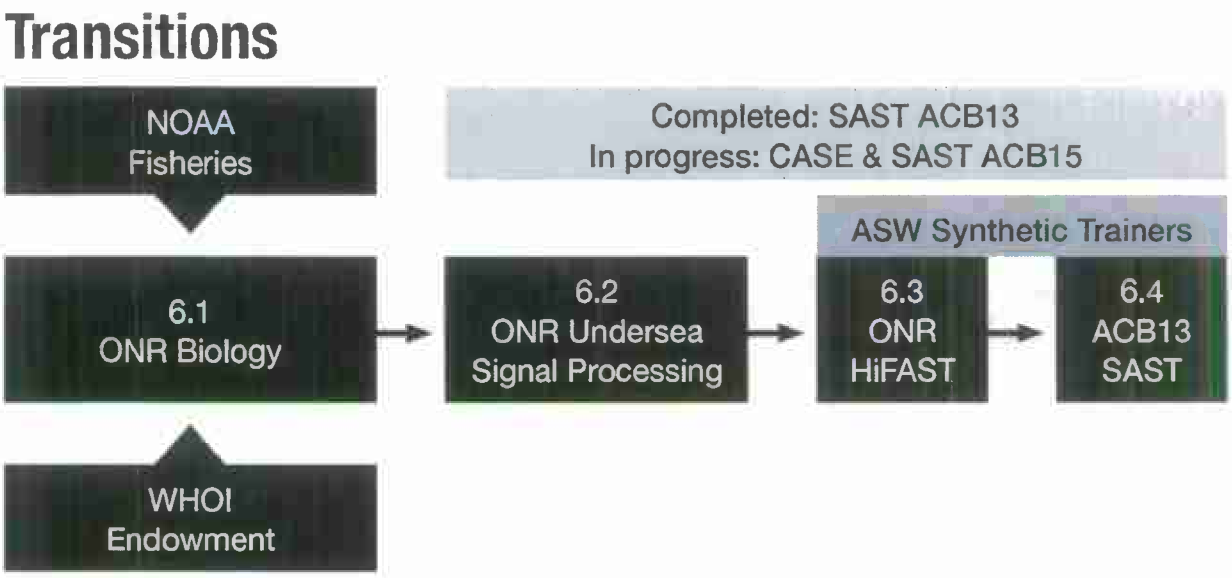


Figure 21. Transition sequence involving data collected in this 6.1 ONR MMB program. The first transition took place in September, 2011 in which HiFAST results (based on the 6.1 and 6.2 results) were transitioned into the Advanced Capability Build 13 (ACB13) SAST system. Work is in progress for transitions to the CASE and ACB15 SAST systems.

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